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An Optoelectrical, Standard CMOS-Based Active Catheter Tracking System for MRI

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Abstract

A fully optical active catheter tracking system compatible with 3T MRI environment is presented. It replaces conducting cables with optical fibers to reduce RF-induced heating problem. Proposed system consists of a MEMS-based microstructure array and an IC driving it. The IC houses an RF receiver block and an optoelectrical power supply. A prototype IC was fabricated in UMC 0.18µm CMOS process. Measurements indicate that the supply unit is able to provide 2.18mA at 1.2V supply, when a laser beam of 80mW power at its source is applied to IC. The system is operational at laser source power levels above 40mW.

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Keywords: MRI; optical powering; CMOS photodiode; electromagnetic actuation; optical MEMS.

1. Introduction

Magnetic resonance imaging (MRI) is commonly used in medicine and related fields due to its high quality imaging, computational flexibility and safety in terms of ionizing radiation [1]. Despite this fact, it is not the imaging method of choice in catheter-based endovascular operations; since presence of long conducting cables required by active catheters may cause heating in magnetic resonance environment [2]. Resulting increase in temperature can be so high that the operation can endanger patient health [3].

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An active catheter system that communicates with the outside world optically to prevent heating was proposed [4] as an alternative to incorporation of decoupling or detuning circuits [5]. This optical system replaces long conducting cables with optical fibers, which are immune to heating due to electromagnetic induction. It is formed of an optical power supply and an MRI receiver, integrated on a single chip, along with an off-chip LED that provides output in optical form. Since the LED has to be powered by the chip, incorporation of this discrete element creates additional strain on area and power limitations, which are already tight. Powering the system in bursts within short intervals can remedy this situation, but this requires accurate synchronization of system and MRI operations [4].

The proposed system employs a MEMS-based microstructure array made of conducting material to provide output. The chip can drive the microstructure array similarly: in MRI environment, the conducting microstructures respond to electric current by deflecting due to Lorentz force induced on them. This actuation can be sensed via optical methods such as wave diffraction grating interferometry. Significance of this approach is that the optical source associated with the output signal is now created externally and is used to sense a mechanical response. Triggering of this mechanical response requires much less power than generating an optical signal within the system. As a result, the burden on the optoelectrical supply is alleviated significantly, allowing it to be designed so that the system can operate continuously. This in turn increases system flexibility and accuracy. It should be noted that the required number of optical waveguides are the same for both cases.

2. System

Block diagram of the system is presented in Fig. 1. As described above, it is formed of the MEMS-based microstructure array and the IC driving it. The optoelectrical power supply and the MRI receiver are integrated in the IC. Storage capacitor of the power supply has to be implemented as a discrete component, since its large capacitance is impractical for integration.

The power supply is formed of a photodiode harvesting power from an incoming optical signal and a dc/dc converter boosting the photodiode voltage to levels required by the receiver. The photodiode is realized using the junctions available in CMOS technology. Despite yielding lower conversion efficiencies, this approach simplifies the process significantly and results in a higher degree of integration. The dc/dc converter is based on two stages of the voltage doubler described in [6]. Stage capacitors are integrated and have a capacitance of 120pF. Off-chip storage capacitance at the output is selected to be 100nF so that the output ripple due to switching is below 50µV. Switches are implemented as MOS switches and are driven by two non-overlapping complementary clock signals of frequency 50MHz, which are generated by a ring oscillator. Since the converter elements are eating away from the power converted by the CMOS photodiode, a simple architecture without regulation blocks is opted for.

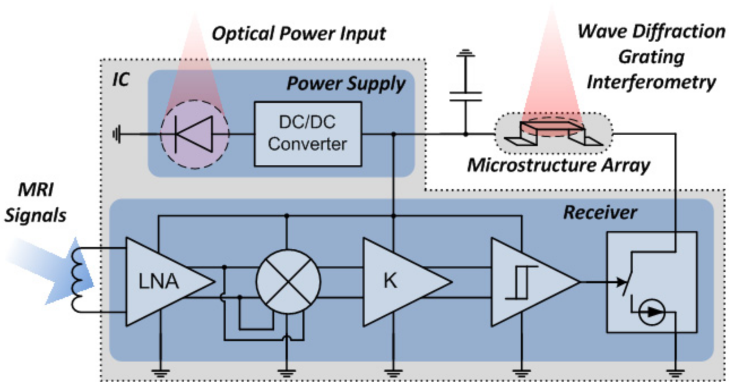

Fig. 1. Block diagram of the whole system.

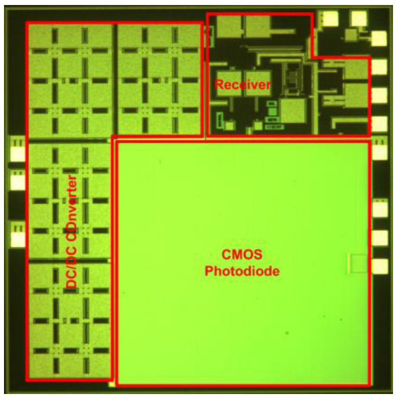

Fig. 2. Micrograph of the integrated circuit.

Diodes are added to the receiver design for ESD protection and integrated dc block capacitors of 10pF are used in between the blocks. MRI signals are sensed by a coil antenna and amplified by an LNA. In MRI localization sequence, two signal components exist, and the difference between their frequencies is a measure of position [1]. A signal that is of this difference frequency is created by self-mixing the amplified signals and filtering out high frequency components subsequently. Comparator block coming after this converts the sine wave into a square wave, which is used to regulate the output of a supply-independent current source, which drives the microstructure array.

Utilization of Lorentz force for microstructure actuation is energy efficient in that it utilizes the strong dc magnetic field (3T) already available in the MRI environment. A unit structure is formed of a reflective surface and a diffraction grating structure hovering above it [7]. The intensity of reflected light is related to the gap height between the surface and the grating. Therefore, a deflection of grating structure would cause a change in light intensity and thus the actuation can be sensed.

3. Experimental Results

At this point, a prototype IC was fabricated with UMC 0.18µm CMOS technology in a die area of 1.5mm x 1.5mm. The photodiode and the receiver cover areas of 1.21mm^2 and 0.3mm^2, respectively. Micrograph of the integrated system is shown in Fig. 2.

A laser source with adjustable power output and wavelength of 650nm was used to generate the power signal; whereas the isolated dc/dc converter measurements were done via electrical sweeps. I-V behavior of the photodiode under different laser power levels are shown together with input I-V characteristics of the dc/dc converter for different output current requirements in Fig. 3. Photodiode dark current is measured to be 29.7pA and the responsivity is calculated to be 0.11 at 60mW of laser power. The dc/dc converter efficiency is 53% around its peak.

An electrical supply was used for isolated receiver measurements. The supply I-V behavior is plotted, along with the output I-V behavior of the overall power supply for different laser power levels, in Fig. 4. It is observed that the receiver is operational for supply voltages above 0.8V corresponding to a minimum laser power level of 40mW. The power supply can provide 2.18mA at a supply voltage of 1.2V when 80mW of laser power is applied. Gain and input referred noise for the LNA are 29dB and 2.5nV/√Hz, respectively. The receiver itself is observed to have an SNR of 48dB. During the system operation, maximum increase in temperature due to optical exposure is measured via an IR thermometer to be 3°C.

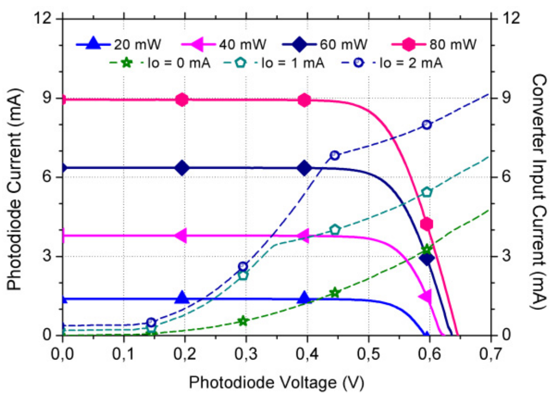

Fig. 4. I-V characteristics of the photodiode for different laser power levels and the input I-V characteristics of the dc/dc converter for different output current biases.

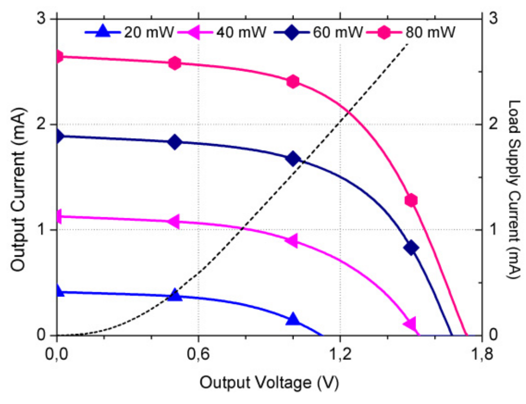

Fig. 3. I-V characteristics of the power supply for different laser power levels and the supply I-V characteristics of the receiver

4. Conclusion

A fully optical, standard CMOS-based active catheter tracking system for MRI aiming to solve heating due to electromagnetic induction is presented. The system is composed of an IC, formed of an optoelectrical power supply and a receiver unit, and a microstructure array driven by it. Power of an externally produced laser beam is harvested by the supply unit to be used by the system. A second externally generated beam is required to sense the Lorentz force induced actuation of the MEMS structures via optical methods.

A functional prototype IC was successfully fabricated with UMC 0.18μm CMOS technology. It was seen that the system is operational at power levels above 40mW, while providing an SNR of 48dB. The power supply can provide 2.18mA at 1.2V output. It was observed that even when no additional heat-sinking structures are present the rise in temperature is at tolerable levels.

Successful fabrication and testing of MEMS microstructures are the next step before all parts of the active catheter tracking system is integrated on the same platform. The said platform is expected to be able to fit into a commercially available 7Fr catheter. Backside of the platform can be utilized for laying out connection paths and mounting of discrete elements to save from space. A 3D coil antenna is desirable for a high quality factor. A large coil can be wrapped around the platform and the optical fibers can be coupled to the optical elements using micromachined MEMS mirrors presented in [8]. Fig. 5 shows an illustration of the completed system.

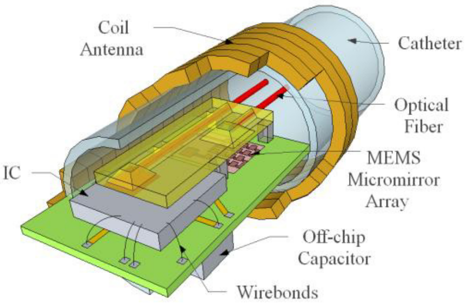

Fig. 5. Illustration of the complete system.

Acknowledgements

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